Year: 2014

The concept of Essential Climate Variables in support of climate research, applications, and policy

Bojinski, Stephan ; Verstraete, Michel ; Peterson, Thomas C ; Richter, Carolin ; Simmons, Adrian ; Zemp, Michael

Abstract: We describe provenance, identification, purpose, uptake and possible evolution of the Essential Climate Variables, a concept to support the data record for understanding climate, as well as mitigating, adapting to or attributing its changes. Climate research, monitoring, prediction and related services rely on accurate observations of the atmosphere, land and ocean, adequately sampled globally and over sufficiently long time periods. The Global Climate Observing System, set up under the auspices of United Nations organizations and the International Council for Science to help ensure the availability of systematic observations of climate, developed the concept of Essential Climate Variables (ECVs). ECV data records are intended to provide reliable, traceable, observation-based evidence for a range of applications, including monitoring, mitigating, adapting to and attributing climate changes, as well as the empirical basis required to understand past, current and possible future climate variability. The ECV concept has been broadly adopted worldwide as the guiding basis for observing climate, including by the UNFCCC, WMO, and space agencies operating Earth Observation satellites. This paper describes the rationale for these ECVs and their current selection, based on the principles of feasibility, relevance and cost-effectiveness. It also provides a view of how the ECV concept could evolve as a guide for rational and evidence based monitoring of climate and environment. Selected examples are discussed to highlight the benefits, limitations and future evolution of this approach. The article is intended to assist programme managers to set priorities for climate observation, dataset generation and related research, for instance within the emerging Global Framework for Climate Services (GFCS). It also helps the observation community and individual researchers to contribute to systematic climate observation, by promoting understanding of ECV choices and the opportunities to influence their evolution.

DOI: https://doi.org/10.1175/BAMS-D-13-00047.1

Originally published at:
Bojinski, Stephan; Verstraete, Michel; Peterson, Thomas C; Richter, Carolin; Simmons, Adrian; Zemp, Michael (2014). The concept of Essential Climate Variables in support of climate research, applications, and policy. Bulletin of the American Meteorological Society, 95(9):1431-1443.
DOI: https://doi.org/10.1175/BAMS-D-13-00047.1

The DOI for this manuscript is doi: 10.1175/BAMS-D-13-00047.1

The concept of Essential Climate Variables in support of climate research, applications, and policy

Authors

Stephan Bojinski[1], World Meteorological Organization (WMO), Geneva, Switzerland

Michel Verstraete, South African National Space Agency (SANSA), Pretoria, South Africa (formerly: European Commission Joint Research Centre, Ispra, Italy)

Thomas C. Peterson, NOAA National Climatic Data Center (NCDC), Asheville, North Carolina, USA

Carolin Richter, Global Climate Observing System (GCOS) Secretariat, World Meteorological Organization (WMO), Geneva, Switzerland

Adrian Simmons, European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK

Michael Zemp, University of Zurich, Zurich, Switzerland

CAPSULE

We describe provenance, identification, purpose, uptake and possible evolution of the Essential Climate Variables, a concept to support the data record for understanding climate, as well as mitigating, adapting to or attributing its changes.

[1]To whom correspondence should be sent (Email: sbojinski@wmo.int; Phone: +41 22 730 8319; Affiliation: World Meteorological Organization, 7bis Avenue de la Paix, CP 2300, 1211 Geneva 2, Switzerland)

ABSTRACT

Climate research, monitoring, prediction and related services rely on accurate observations of the atmosphere, land and ocean, adequately sampled globally and over sufficiently long time periods. The Global Climate Observing System, set up under the auspices of United Nations organizations and the International Council for Science to help ensure the availability of systematic observations of climate, developed the concept of Essential Climate Variables (ECVs). ECV data records are intended to provide reliable, traceable, observation-based evidence for a range of applications, including monitoring, mitigating, adapting to and attributing climate changes, as well as the empirical basis required to understand past, current and possible future climate variability. The ECV concept has been broadly adopted worldwide as the guiding basis for observing climate, including by the UNFCCC, WMO, and space agencies operating Earth Observation satellites.

This paper describes the rationale for these ECVs and their current selection, based on the principles of feasibility, relevance and cost-effectiveness. It also provides a view of how the ECV concept could evolve as a guide for rational and evidence-based monitoring of climate and environment. Selected examples are discussed to highlight the benefits, limitations and future evolution of this approach.

The article is intended to assist programme managers to set priorities for climate observation, dataset generation and related research, for instance within the emerging Global Framework for Climate Services (GFCS). It also helps the

observation community and individual researchers to contribute to systematic climate observation, by promoting understanding of ECV choices and the opportunities to influence their evolution.

Observations are fundamental to advancing scientific understanding of climate (Doherty et al. 2009; Shapiro et al. 2010) and delivering the vetted, timely and purposeful climate information needed to support decision-making in many sectors. Observations and monitoring are key elements of the emerging Global Framework for Climate Services (WMO 2011a) and more generally support climate research, the assessment of climate change, and the development of policy responses (Figure 1). For these purposes, observational datasets in general need to be traceable to quality standards, be readily interpretable and freely available, and cover sufficiently long periods, for example the 30 years traditionally used for calculating climate normals (WMO 2011b). Transparency in the generation of climate datasets is essential for ensuring the credibility of the climate record (UN 2012).

In the 1990s, gaps in knowledge of climate and declining core observational networks in many countries (Houghton et al. 2012) led to calls for systematic observation of a limited set of critical variables. To provide guidance, the Global Climate Observing System (GCOS) programme developed the concept of "Essential Climate Variables" (ECVs) which has since been broadly adopted in science and policy circles.

In this article, we define the ECV concept and describe its provenance, scientific rationale and uptake. We also discuss challenges and opportunities concerning the ECV concept and its possible evolution, in particular with regard to the GCOS-led process of assessment, adequacy, and implementation of global observing systems for climate.

WHAT ARE THE ECVs?

An ECV is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of the Earth's climate. ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to guide mitigation and adaptation measures, to assess risks and enable attribution of climatic events to underlying causes, and to underpin climate services. The current list of ECVs is specified in the *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC* (GCOS-138[2] 2010) and reproduced in Table 1.

More than variables: The ECV concept

The ECVs must not be understood as a select group of stand-alone variables; they are part of a wider concept (Figure 2). ECVs are identified based on the criteria of:

- Relevance: the variable is critical for characterizing the climate system and its changes;
- Feasibility: observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods; and

[2] All references to GCOS reports use the original GCOS publication number, and the year of publication, for easier reference. All GCOS reports are available at http://www.wmo.int/pages/prog/gcos/index.php?name=Publications

- Cost-effectiveness: generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

To make practical use of the ECVs, guidance and best practices are needed to enable and support the generation of high-quality, traceable ECV data records (see details in Fig. 2). The ECV concept accommodates mixed or changing observing system technologies and is therefore conducive to meeting user needs for information over the long term. It helps distil a complex field into a manageable list of priorities and related actions (GCOS-138 2010).

PROVENANCE

Some twenty years ago, the international community began exploring a more coordinated approach to observing climate on a global scale. The GCOS programme, founded in 1992 by WMO, IOC/UNESCO, UNEP and ICSU, was mandated to define objectives and recommend coordinated action for a global observing system for climate, building on and enhancing existing systems (GCOS-14 1995; Houghton et al. 2012). The initial Plan called for a system based on (i) fundamental scientific priorities and (ii) prioritized observational requirements, informed by scientific and technical progress and evolving user needs. It identified "principal observations" to be addressed by a set of space missions, noting earlier work in support of short-term climate predictions (NRC 1994).

Priorities were further elaborated by exploring which physical variables or combination of variables would be most suitable for long-term climate monitoring (Karl 1996, and references therein, notably Trenberth 1995). Observational priorities were formulated recognising the capabilities of current or expected observing systems.

Subsequently, the international terrestrial community identified "key variables" describing the biosphere, hydrosphere and cryosphere (GCOS-32 1997) based on measurement practicality and the priority for climate. These variables were deemed the minimal set for which data records were absolutely necessary, recognizing that other, "secondary", variables were also important for context or interpretation.

The term 'Essential Climate Variables' was first introduced in the *Second Report on the Adequacy of Global Observing Systems for Climate in Support of the UNFCCC* (GCOS-82 2003), spanning the atmospheric, oceanic and terrestrial domains. In their response to this report, Parties (signatory states) of the UNFCCC emphasized the principle of free and unrestricted exchange for ECV datasets, adopted an expanded set of GCOS Climate Monitoring Principles and requested the GCOS programme to plan implementation (UNFCCC 2004).

Subsequent reporting and planning, starting with the first Implementation Plan (GCOS-92 2004), used the ECVs as a guiding framework. Indicative requirements for accuracy, spatial and temporal resolution and other characteristics of ECV datasets were specified for satellite-based datasets (GCOS-107 2006; GCOS-154 2011). Guidelines were also developed for generating ECV data records in general, emphasizing the importance of calibration and validation, documentation, and self and independent assessments (GCOS-143 2010). The twenty Climate Monitoring Principles, developed based on the original set of ten adopted by the UNFCCC in 1999, provide guidance for observing-system operations (GCOS-138 2011).

UPTAKE

Science and policy circles have widely endorsed the ECV concept. The Parties to the UNFCCC acknowledged the need to act upon the plans for implementation (GCOS-92 2004; GCOS-138 2010). Guidelines for their reporting on national programmes contributing to global climate observation are structured along the ECVs (UNFCCC 2008). In its planning of global observation for weather, water and climate applications, WMO addresses the ECVs and recognizes GCOS assessment and planning documents as statements of guidance.

The ECVs have been identified as a key element of the observations and monitoring pillar of the GFCS (WMO 2011a). European regulation on initial operation of environmental services within the Copernicus initiative (formerly GMES) builds upon the ECVs for its climate service component (European Union 2010). Some countries use the ECV concept to identify national climate observing networks and data records, and to improve the legal and financial basis for continuity (Seiz and Foppa 2007).

Satellite agencies have responded strongly to the concept, through the Committee on Earth Observation Satellites (CEOS 2008) and more recently through the broadly-developed Architecture for Climate Monitoring from Space (Dowell et al. 2013). ESA launched the Climate Change Initiative aimed at the generation of satellite-derived ECV datasets based on historical data holdings (Hollmann et al. 2013; ESA 2013). EUMETSAT (2011) responded, by deriving ECV records (Schulz et al. 2009) and, along with the Japan Meteorological Agency, by reprocessing wind and other data from their geostationary satellites. Agencies from the USA, China and other countries engage in related initiatives such as the Global Space-based Inter-Calibration System (GSICS; Hewison et al. 2013) and the Sustained, Coordinated Processing of Environmental Satellite Data for Climate Monitoring (SCOPE-CM; Lattanzio et al. 2012).

Annual statements on the *State of the Global Climate* are now structured around the ECVs (Blunden and Arndt 2013; this reference includes a range of average multi-decadal ECV time series and a brief account of ECV provenance), and so is a recent report on global climate events during the decade 2001-2010 (WMO 2013). Most of the essential needs for sustained observation identified by the World Climate Research Programme (WCRP) and enabling the work of the Intergovernmental Panel on Climate Change (IPCC) are based on the ECVs (Doherty et al. 2009).

Systematic assessment and evaluation of ECV datasets at the international level is a general need, and has begun (WCRP 2011; Stubenrauch et al. 2013).

In summary, identifying ECVs and associated guidance has encouraged scientists and observing system operators to put more focus on these variables. It has stimulated the engagement of national and international organizations and funding agencies to support work on the variables. It has also helped many nations to make commitments to support systematic, sustained climate records.

The variable-based approach has been adopted more broadly as a basis for prioritized requirements setting and focused, coordinated action. In particular, the ocean and biodiversity communities have identified Essential Ocean Variables (UNESCO 2012) and Essential Biodiversity Variables (Pereira et al. 2013). Furthermore, many ECVs may also be useful for addressing applications that are not directly climate-related, for instance in support of other Societal Benefit Areas of the GEOSS (e.g., Hollingsworth et al. 2005).

DISCUSSION AND ILLUSTRATION

The ECV concept supports observing system planning, network design and operation, and climate dataset generation, but is not without its challenges.

Observing system planning and resourcing

By their very nature, ECVs (or quantities closely related to them from which ECV datasets can be derived) must be observed as a matter of priority, in a way that meets requirements. The ECV concept guides the specification of observing networks and archiving systems, and the arrangements for monitoring their performance. However, meeting climate standards implies continuing investments in instrumentation and in the generation, validation and inter-comparison of datasets. Existing infrastructure, often in support of weather forecasting, may need upgrading to meet the more exacting needs of some climate applications. Despite progress in recent years, much of the global infrastructure for acquiring and archiving climate observations and for delivering related climate datasets and services remains fragile and incomplete (GCOS-129 2009; WMO 2011a).

Further optimising the design of an integrated global climate observing system remains important (Trenberth et al. 2012). The GCOS programme recognised a hierarchy of observational networks and systems, comprising comprehensive, baseline and reference networks (Houghton et al. 2012; Seidel et al. 2009) based on assumptions of spatial sampling needs (e.g., Peterson et al. 1997). However, a more systematic approach is needed to observing-system design studies, including impact experiments, using guidance from the numerical weather prediction community (WMO 2012) and recognising that many observations will continue to serve both weather and climate purposes. Such studies have to take account of intrinsic climate variability and limits to predictability (Meehl 2009; Hoskins 2013).

Many research activities are important to systematic ECV observation since (i) they provide supplemental observations, (ii) they seek better ways of meeting targets for accuracy, and (iii) they pioneer capabilities to measure new variables. Yet, projects or systems based on research funding are generally not designed for transition to sustained monitoring of variables globally and over long time periods, often leading to partial, haphazard, intermittent coverage (Keeling 1998; Nisbet 2007; Wunsch et al. 2013). Recognition of variables as ECVs has helped alleviate issues and foster transition of research-based observational activities into a more sustained framework (e.g., WGMS 2008, ICOS 2013).

Generating ECV datasets

Long-term instrument-level datasets, such as satellite-based "Fundamental Climate Data Records" (calibrated datasets at nominal instrument-specific resolution), are the critical basis for generating ECV datasets. Many steps need to be carefully considered, for which GCOS-143 (2010) provides general guidance. Quality assessment and peer-review of datasets are very important (see Side Bar). Providers of climate datasets should, where possible, meet community-specific needs for representing data, such as in suitable gridded formats with information on uncertainty to facilitate model-observation comparisons (Gomez-Navarro et al. 2012).

Reanalysis

Reprocessing past observations of atmosphere, ocean and land using data assimilation methods as developed for numerical weather prediction and seasonal forecasting has become an important information source on recent climate variations (Dee et al. 2014) and for assessing climate models (Gleckler et al. 2008). Such reanalysis is both a consumer and, as featured in the State of the Climate report (Blunden and Arndt 2013), a contributor to ECV datasets. ERA-Interim, for example, provides datasets for atmospheric surface and upper-air ECVs and other ECVs such as ozone and ocean-wave state, but its assimilating model uses specified sea-surface temperatures, sea-ice concentrations and various land surface fields and radiative gas distributions. Extension to provide analysis of atmospheric composition ECVs is discussed by Dee et al. (2014). Ocean and land reanalyses provide datasets on variables such as sub-surface ocean temperature and soil moisture, but in turn utilize meteorological forcing fields from atmospheric reanalysis or other sources. Capability for analysing other domains continues to improve, as shown by Balmaseda et al. (2013) for ocean reanalysis, and with further development of coupled data assimilation, the number of reanalysis-based ECV datasets is expected to rise.

The quality and applicability of the comprehensive ECV datasets provided by reanalysis vary geographically, with height, over time, and from one variable to another, and can be difficult to quantify. For example, Compo et al. (2011) use ensemble data assimilation to estimate uncertainty associated with flow-dependent predictability, but this does not obviate the need for additional, observation-related diagnostic information that supplements gridded reanalysis datasets (Dee et al. 2011). Comparison of an ECV dataset from reanalysis with an alternative derived directly from observations as outlined in the Side Bar can provide reassurance as to the quality of both (Simmons et al. 2010).

Examples for terrestrial ECVs

Many terrestrial ECVs, such as river runoff and soil moisture, are of vital direct societal importance, and many are inherently more heterogeneous than their atmospheric and oceanic counterparts. Establishing international coordination and measurement standards has been more difficult for terrestrial than for other ECVs. Yet, progress has been made (GCOS-129 2009) and benefits of designating variables as ECVs have been realised. Two examples are briefly discussed.

The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) is a measure of the productivity of the continental biosphere and thus of utmost interest. Identification as an ECV helped focus the attention of the scientific community, and multiple teams developed methods to retrieve values from remote sensing in the solar spectral range. This led to the generation of multiple datasets, stimulated the organization of field campaigns to acquire *in situ* measurements, and prompted CEOS to address discrepancies in the context of its calibration and validation working group. Efforts to harmonize FAPAR datasets are ongoing (e.g., Ceccherini et al. 2013). Yet, despite intense research and sustained efforts to establish standards and best practices (e.g., on validation, Widlowski 2010), no institution has proposed to be, or been identified to serve, as the central point of contact for the worldwide compilation, archiving and distribution of FAPAR datasets.

Glaciers and ice caps have been recognized as an ECV since they are clear indicators of climate change and important contributors to global sea level changes, regional water cycles, and local hazards. Changes in glacier length, area, volume and mass are the key variables. Records date back to the 17th century and trans-national compilations of such data were initiated in the late 19th century (WGMS 2008). Loss of glacier mass due to surface air temperature and precipitation changes contributes an estimated 30% to total observed sea-level change (Gardner et al. 2013) – underscoring the need to understand and observe the physical interplay of atmospheric, ocean and terrestrial ECVs.

Recognizing glaciers as an ECV has helped secure sustained funding for the World Glacier Monitoring Service (WGMS) and additional funding for capacity building promoting the resumption of systematic observation in some countries (MeteoSwiss 2013). Terminology standards and best observational practices have also been developed (Cogley et al. 2011; Zemp et al. 2013).

Essential fluxes

It has been proposed that fluxes (e.g., of energy, water, carbon) be included in the ECV list, mainly since they are essential for understanding the cyclical processes of the climate system. Fluxes can sometimes be derived from measured gradients of ECVs, for example by analysing atmospheric humidity profiles obtained from soundings, or by eddy covariance measurements of trace gases. Generally, and especially at large scales, however, fluxes are not directly observable. They are inferred from a combination of observations, model simulations and assumptions about the permeability of interfaces, for example for estimating the net flux of methane over permafrost areas using biogeochemical models and observations (Zhang et al. 2012). Clearer focus on how to quantify these fluxes and to agree on consistent terminology and measurement principles should improve the description of exchange processes at interfaces, and facilitate understanding of biogeochemical cycles.

Consistency of the ECV list

Consistently applying the selection criteria for ECVs has been a challenge due to their diversity. This extends to adding or removing variables: the importance of many other variables has long been recognized (GCOS-32 (1997) identified as many as 70 key variables to characterize land surfaces), but their adoption as ECVs has been hampered by other considerations, for instance in the case of land surface temperature, complexity of interpretation and limited utility for climate monitoring. Some variables have been initially 'carried over' as ECVs because of their historical importance and availability, though they might not have been selected in the absence of such a legacy (e.g., chlorophyll concentration in the top ocean layer).

Diverse requirements

Different observation requirements for the same ECV from different application communities need to be recognized and reconciled, where possible. For example, numerical weather forecasting and seasonal prediction require near-real-time access to observations of atmospheric and surface variables to optimally predict (possibly extreme) events. Some of the variables may also be of great interest for climate adaptation or trend studies. These applications have quite different requirements for spatial and temporal resolution, timeliness of data delivery, absolute accuracy, measurement stability and length of data record.

Similarly, requirements for biological variables such as the Leaf Area Index, which measures the surface of leaf material in plant canopies, are quite different for constraining a climate model than for managing agricultural systems against a regional climate change backdrop: horizontal resolution of global climate models is generally on the order of 50km and would require a Leaf Area Index dataset at this order of spatial resolution, whereas for agricultural management, details on a resolution as fine as 1km or less may be necessary. In the same vein, requirements for measuring air temperature for estimating urban heat stress differ from those for quantifying multi-decadal trends in regional temperature.

Moreover, the thematic separation of ECVs into three geophysical domains has led to the setting of somewhat incompatible specifications for variables that are physically linked. For example, in GCOS-154 (2011) observational requirements set for the ECV "surface albedo" (a joint property of the land and the overlying atmosphere; GCOS TP-1 2007; Lattanzio et al. 2013) are not compatible with the requirements set for aerosols and clouds, which are drivers of the atmospheric radiative properties. Such inconsistencies require further attention.

HOW SHOULD THE ECV CONCEPT EVOLVE?

The ECV concept has proven useful to scientists, observing system operators, programme planners and policy-makers, but issues related to consistency, data curation, resources, requirements, and review of the ECV concept have been identified. How should the concept evolve over the coming decades? The following paragraphs discuss additional drivers for a progressive evolution and a process for managing it.

Data curation and stewardship

Many communities have risen to the challenge of long-term data management and stewardship. They have designed and built unique, worldwide facilities to preserve essential heritage information in their respective fields including seed banks to preserve biodiversity (Fowler 2008), powerful data infrastructures to support large-scale particle physics experiments (Bird 2011) and the UNESCO world cultural heritage record (UNESCO 1972). Such facilities require institutional commitments, agreements on sharing resources and common data management standards.

Elements of a global infrastructure for climate dataset curation and stewardship are in place, partly based on data centres recognized within the ICSU World Data System (ICSU 2013). However, the data policies of many providers still prevent free and open data access to ECV datasets, despite progress in response to repeated calls for change (Uhlir et al. 2009). Intellectual property issues that compromise open access to climate records (Nelson 2009) should be overcome by introducing data identifiers (such as DOIs) as standard practice, thus incentivizing data sharing through recognition of authorship. Restrictions stemming from a perceived commercial or strategic value of climate data are more difficult to resolve.

Also, although the Global Observing Systems Information Center data portal hosted by the US National Climatic Data Center (http://www.gosic.org) facilitates discovery and access to ECV products, gaps remain in providing single access points to well-documented datasets in common data formats for the complete range of ECVs. New cost-sharing arrangements, e.g. by levying observation activities to ensure long-term stewardship, should be explored.

Broadening the Earth observation basis

Over the coming decade, wider availability of low-cost sensor technology will contribute to higher spatial and temporal sampling of the near-surface environment (e.g., through deployment in urban environments, transport vehicles, drones, or through “citizen observations”). Although trade-offs between data quality and volume will have to be made, such observations could be beneficial for tracking impacts of, or exposure to, climatic and other environmental hazards, and thereby help building ECV datasets. Broad deployment of observing technology could also raise public awareness of environmental monitoring and eventually lead to smarter environmental decision-making.

Beyond climate

Today's climate models still have limited representations of the biogeochemical cycles (notably carbon). Decades from now, global models of the Earth system will likely simulate agricultural and industrial production, transport, consumption, economic flows, and demography. Socio-economic variables such as gross domestic product, rate of mortality, disease incidence and transport routes would be considered to be as essential as the current set of physical, chemical and biological variables. Data on some of these socio-economic variables are already needed to model anthropogenic emissions of greenhouse gases and other pollutants, to monitor and control other environmental risks and to provide climate services. Much more will be needed as modelling capabilities expand. Progress in data assimilation and observation technology is expected to go hand-in-hand with this development. Climate and environment information will become increasingly important for understanding and predicting the evolution of markets and influence financial strategies. These communities may evolve from mere customers of information to also directly supporting the generation, archiving and distribution of basic data.

Process

Given its broad uptake, further development of the ECV concept needs to be well managed, based on regular reviews and updates of guidance. The process that has been developed by the GCOS programme involves a variable-based assessment and implementation cycle that is shown in generic, schematic form in Figure 3. It builds on the existence of an identified **pool of climate-relevant variables** – the ECVs and other variables that are candidates for consideration as ECVs depending on relevance, feasibility and cost-effectiveness. The cycle comprises:

- **Assessment of adequacy** of observing systems, ECV datasets, and scientific and technological developments (the "Foundations" in Fig. 2), with implications for the list of ECVs;
- **Implementation planning** based on an updated set of ECVs and guidance material ("Guidance", Fig. 2), identifying the required actions related to observing system design, dataset generation and data stewardship;
- Responses by the agents for implementation (e.g., observing system operators), seen most immediately by users in the **generation and exploitation of datasets** that underpin products, user applications, and services.

Fig. 3 goes beyond current GCOS practice in also recognizing that some data records should be designated to be part of the **climate heritage record**, and should be preserved in dedicated archives. The heritage record should include datasets that have been superseded by new science or technology; where possible these datasets should be maintained in parallel with new observations during a period of overlap sufficient to ensure a traceable record, and some should be continued for as long as they usefully serve as a baseline for climate assessments.

The GCOS reporting and planning documents that result from the assessment and implementation cycle are based on broad community engagement. This involves scientific workshops that draw on lessons learnt from the IPCC assessment process, scrutiny by its co-sponsored expert panels for atmosphere, ocean and land (Houghton et al. 2012), open public review and response to comments, and formal acceptance by the Steering Committee for GCOS, to which members are appointed by the programme sponsors. The process gains legitimacy through acceptance by the sponsors, the Parties to the UNFCCC and others, including the various national and international agents for implementation without whom progress could not be made.

The 'essential' character of the ECV list has been one of its strengths, calling for prudence in its expansion. The roughly six-year period adopted by GCOS for the cycle illustrated in Fig. 3 has tended to follow that of the IPCC assessment reports, though arguably it should be a little longer. Observation requirements for ECV datasets must recognise the needs of the range of applications. Although a holistic approach to setting them is desirable, the user requirements for ECV datasets will not in general be consistent among each other. In any case, GCOS requirements are of indicative nature, and more refined user requirements have to be developed for specific observing missions and dataset generation initiatives (e.g., Hollmann et al. 2013).

Addition of fluxes and socio-economic variables to the ECVs would require a departure from the current distinction by geophysical domains. Questions to address would include, for example, whether the GCOS climate monitoring principles can be straightforwardly adapted to guide "observing systems" for socio-economic parameters, or whether the same principles for dataset documentation and reprocessing can be applied to datasets describing population and wealth distribution. Ways of defining and presenting the ECV concept will have to evolve.

IN CONCLUSION

The ECV concept has been successful and should continue to guide the observation community in enabling evidence-based climate monitoring, science, and services. The ECV concept addresses public demands for transparency in environmental decision-making (UN 2012; Major Groups 2012). We nevertheless realize the limits to rationality and objectivity in such decisions (Nilsson and Dalkmann 2001) even if optimal observation-based evidence – say for environmental degradation – is available.

The ECV concept is flexible vis-à-vis changing priorities, application needs and scientific and technological innovation. Priorities remain essential; the ECV concept has provided guidance in this regard. It may serve as a blueprint for communities of practice in other societal benefit areas of the GEOSS as they assess evolving data needs and required actions for observing the Earth system.

The climate community at large is invited to participate in the discussion of further evolution of the ECV concept. The process lives from consensus and active participation. Strong connections to those involved in climate research, in particular through the WCRP, and in applications remain essential. The GCOS programme has already begun a new assessment phase, which will draw in part on conclusions drawn from the 5th IPCC Assessment Report. Based on its evaluation of progress and adequacy, the next issue of the implementation plan for the global observing system for climate will be developed for 2016. The GCOS Secretariat (gcosjpo@wmo.int) should be contacted for further information.

ACKNOWLEDGMENTS

We thank Paul Mason who led the development of many of the key GCOS documents contributing to the ECV concept. We also thank Alan Belward, Eric Lindstrom and reviewers for comments on earlier versions of this article.

REFERENCES

Aguilar, E., I. Auer, M. Brunet, T. C. Peterson, and J. Wieringa, 2003: *Guidelines on Climate Metadata and Homogenization.* WCDMP-No. 53, WMO-TD No. 1186, World Meteorological Organization, Geneva, 55 pp.

Balmaseda, M. A., K. Mogensen, and A.T. Weaver, 2013: Evaluation of the ECMWF ocean reanalysis system ORAS4. *Q.J.R. Meteorol. Soc*., 139: 1132–1161. doi: 10.1002/qj.2063

Bates, J. and J. Privette, 2012: A maturity model for assessing the completeness of climate data records. *Eos, Transactions American Geophysical Union*, **93** (44), page 441, 30 October 2012. doi: 10.1029/2012EO440006

Bird, I., 2011: Computing for the Large Hadron Collider. *Annual Review of Nuclear and Particle Science*, 61: 99-118, November 2011.

Blunden, J., and D. S. Arndt, Eds., 2013: State of the Climate in 2012. *Bull. Amer. Meteor. Soc*., **94** (8), S1–S238.

Ceccherini, G., N. Gobron, and M. Robustelli, 2013: Harmonization of Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) from Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and Medium Resolution Imaging Spectrometer Instrument (MERIS). *Remote Sens.* **2013**, *5*, 3357-3376. doi:10.3390/rs5073357

CEOS, 2008: *The Earth Observation Handbook – Climate Change Special Edition 2008.* ESA SP-1315, 265pp.

Christy, J.R., R. W. Spencer , W.B. Norris, W.D. Braswell, and D.E. Parker, 2003: Error estimates of version 5.0 of MSU-AMSU bulk atmospheric temperatures. *J. Atmos. Ocean. Tech.* **20**:613–629.

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M.C. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, , H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, and S.J. Worley, 2011: The Twentieth Century Reanalysis Project. *Q.J.R. Meteorol. Soc.*, **137**, 1–28. doi: 10.1002/qj.776

Dee, D.P., E. Källén, A.J. Simmons, and L. Haimberger, 2011: Comments on "Reanalyses Suitable for Characterizing Long-Term Trends". *Bull. Amer. Meteor. Soc.*, **92**: 65-70. doi: 10.1175/2010BAMS3070.1

Dee, D. P., M. Balmaseda, G. Balsamo, R. Engelen, A. J. Simmons, and J.-N. Thépaut, 2014: Toward a consistent reanalysis of the climate system. *Accepted for publication in Bull. Amer. Meteor. Soc.*

Doherty, S.J., S. Bojinski, A. Henderson-Sellers, K. Noone, D. Goodrich, N.L. Bindoff, J.A. Church, K.A. Hibbard, T.R. Karl, L. Kajfez-Bogataj, A.H. Lynch, D.E. Parker, C. Prentice, V. Ramaswamy, R.W. Saunders, M. Stafford-Smith, K. Steffen, T.F. Stocker, P.W. Thorne, K.E. Trenberth, M. Verstraete, and F.W. Zwiers, 2009: Lessons learned from the IPCC AR4 - Scientific Developments Needed To Understand, Predict, And Respond To Climate Change. *Bull. Amer. Meteor. Soc.*, **90**, 497-513. doi:10.1175/2008BAMS 2643.1

Dowell, M., P. Lecomte, R. Husband, J. Schulz, T. Mohr, Y. Tahara, R. Eckman, E. Lindstrom, C. Wooldridge, S. Hilding, J.Bates, B. Ryan, J. Lafeuille, and S. Bojinski, 2013: *Strategy Towards an Architecture for Climate Monitoring from Space*. Pp. 39. This report is available at: http://www.ceos.org; http://www.wmo.int/sat; http://www.cgms-info.org

ESA, 2013: *Response by ESA to GCOS – Results of the Climate Change Initiative Requirements Analysis*. CCI-PRGM-EOPS-TN-13-0008, available at http://46.137.76.174/?q=webfm_send/80

EUMETSAT, 2011: *EUMETSAT Strategy: A Global Operational Satellite Agency at the Heart of Europe*. EUMETSAT COR.02-v1, October 2011, available at http://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=PDF_BR_COR02_EN&RevisionSelectionMethod=LatestReleased&Rendition=Web

European Union, 2010: *Regulation (EU) No 911/2010 of the European Parliament and of the Council of 22 September 2010 on the European Earth monitoring programme (GMES) and its initial operations (2011 to 2013)*. OJ L 276, 20.10.2010, p.1, available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32010R0911:EN:NOT

Gardner, A. S., G. Moholdt, J.G. Cogley, B. Wouters, A. Arendt, J. Wahr, E. Berthier, R. Hock, W.T. Pfeffer, G. Kaser, S. Ligtenberg, T. Bolch, M. Sharp, J. Hagen, M. van der Broeke, and F. Paul, 2013: A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009. *Science*, **340**(6134), 852–857. doi:10.1126/science.1234532

Folland, C.K., D. Parker, R.W. Reynolds, S.C. Sherwood, and P.W. Thorne, 2006: What measures can be taken to improve the understanding of observed changes? In: Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences. T. R. Karl, S. J. Hassol, C. D. Miller, and W. L. Murray, Eds. *A Report by the Climate Change Science Program and the Subcommittee on Global Change Research*, Washington, DC, USA.

Fowler, C., 2008: *The Svalbard Global Seed Vault: Securing the Future for Agriculture*. The Global Crop Diversity Trust, 26 Feb 2008, available at http://www.croptrust.org/documents/Svalbard%20opening/New%20EMBARGOED-Global%20Crop%20Diversity%20Trust%20Svalbard%20Paper.pdf

GCOS documents available at http://www.wmo.int/pages/prog/gcos/index.php?name=Publications:

GCOS-14, 1995: *Plan for the Global Climate Observing System*

GCOS-32, 1997: *GCOS/GTOS Plan for Terrestrial Climate-related Observations*

GCOS-82, 2003: *Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC*

GCOS-92, 2004: *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC*

GCOS-107, 2006: *Systematic Observation Requirements for Satellite-based Products for Climate Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC*

GCOS-129, 2009: *Progress Report on the Implementation of the Global Observing System for Climate in support of the UNFCCC 2004-2008*

GCOS-138, 2010: *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)*

GCOS-143, 2010: *Guideline for the Generation of Datasets and Products Meeting GCOS Requirements*

GCOS-154, 2011: *Systematic Observation Requirements for Satellite-based Products for Climate Supplemental details to the satellite-based component of the*

Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC - 2011 Update

GCOS TP-1, 2007: *GCOS AOPC/TOPC Joint Working Group on Land-Surface/Atmosphere Issues*. First meeting, European Commission Joint Research Centre, Ispra, Italy, 14-15 February 2007.

Gleckler, P., K. E. Taylor, and C. Doutriaux, 2008: Performance Metrics for climate models. *J. Geophys. Res.*, **113**, D06104. doi:10.1029/2007JD008972

Gomez-Navarro, J.J., J. P. Montávez, S. Jerez, P. Jiménez-Guerrero, and E. Zorita, 2012: What is the role of the observational dataset in the evaluation and scoring of climate models? *Geophysical Research Letters*, **39**, L24701. doi:10.1029/2012GL054206

ICSU, 2013: *The International Council of Scientific Unions World Data System*: http://www.icsu-wds.org/our-members/membership-categories/regular-members

Hewison, T., X. Wu, F. Yu, Y. Tahara, X. Hu, D. Kim, and M. Koenig, 2013: GSICS Inter-Calibration of Infrared Channels of Geostationary Imagers Using Metop/IASI. *IEEE Transactions on Geoscience and Remote Sensing*, **51**(3), March 2013. doi: 10.1109/TGRS.2013.2238544

Hollingsworth, A., S. Uppala, E. Klinker, D. Burridge, F. Vitart, J. Onvlee, J.W. de Vries, Ad de Roo, and C. Pfrang, 2005: The transformation of Earth-system observations into information of socio-economic value in GEOSS. *Q. J. R. Meteor. Soc.*, **131**, 3493-3512.

Hollmann, R., C.J. Merchant, R. Saunders, C. Downy, M. Buchwitz, A. Cazenave, E. Chuvieco, P. Defourny, G. de Leeuw, R. Forsberg, T. Holzer-Popp, F. Paul, S. Sandven, S. Sathyendranath, M. van Roozendael, and W. Wagner, 2013: The ESA Climate Change Initiative: satellite data records for essential climate variables. *Bull. Amer. Meteor. Soc.* **94** (10), 1541-1552, doi: 10.1175/BAMS-D-11-00254.1

Hoskins, B., 2013: The potential for skill across the range of the seamless weather-climate prediction problem: a stimulus for our science. *Q.J.R. Meteor. Soc.*, **139**, 573-584.

Houghton, J., J. Townshend, K. Dawson, P. Mason, J. Zillman, and A. Simmons, 2012: The GCOS at 20 years: the origin, achievement and future development of the Global Climate Observing System. *Weather*, **67**, No. 9.

ICOS (Integrated Carbon Observation System), 2013: *A European infrastructure dedicated to high-precision monitoring of greenhouse gas fluxes*. http://www.icos-infrastructure.eu

Karl, T., Editor, 1996: *Long-term Climate Monitoring by the Global Climate Observing Syste*m, Kluwer Academic Publishers, Dordrecht (also appeared in *Climatic Change* Volume 31, Nos 2-4, 1995), 518pp.

Kent, E.C., and A. Kaplan, 2006: Toward Estimating Climatic Trends in SST. Part III: Systematic Biases. *J. Atmos. Oceanic Technol.*, **23**, 487–500.

Lawrimore, J. H., M. J. Menne, B. E. Gleason, C. N. Williams, D. B. Wuertz, R. S. Vose, and J. Rennie, 2011: An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3. *J. Geophys. Res.*, 116, D19121. doi:10.1029/2011JD016187

Keeling, C.D., 1998: Rewards and Penalties of Monitoring the Earth. *Annu. Rev. Energy Environ. 1998,* **23**:25–82.

Lattanzio, A., J. Schulz, J. Matthews, A. Okuyama, B. Theodore, J.J. Bates, K.R. Knapp, Y. Kosaka, and L. Schüller, 2013: Land Surface Albedo from Geostationary Satellites – A Multiagency Collaboration within SCOPE-CM. *Bull. Amer. Meteor. Soc.*, **94**, 205-214. doi 10.1175/BAMS-D-11-00230.1

Los, S.O., G.J. Collatz, P.J. Sellers, C.M. Malmström, N.H. Pollack, R.S. DeFries, L. Bounoua, M.T. Parris, C.J. Tucker, and D.A. Dazlich, 2000: A Global 9-yr Biophysical Land Surface Dataset from NOAA AVHRR Data. *J. Hydrometeor.*, **1**, 183–199.

Major Groups, 2012: *Rio+20 Common Statement,* Stakeholder Forum of the Earth Summit 2012, 20-22 June 2012, Rio de Janeiro, Brazil, available at http://www.stakeholderforum.org/fileadmin/files/Major%20Groups%20common%20statement.pdf

Mears, C.A., M.C. Schabel, and F.J. Wentz, 2003: A reanalysis of the MSU channel 2 tropospheric temperature record. *J. Clim.*, 16:3650–3664.

Meehl, G.A., L. Goddard, J. Murphy, R.J. Stouffer, G. Boer, G. Danabasoglu, K. Dixon, M.A. Giorgetta, A.M. Greene, E. Hawkins, G. Hegerl, D. Karoly, N. Keenlyside, M. Kimoto, B. Kirtman, A. Navarra, R. Pulwarty, D. Smith, D. Stammer, and T. Stockdale, 2009: Decadal prediction: Can It Be Skillful? *Bull. Amer. Meteor. Soc.*, **90**, 1467-1485. doi:10.1175/2009BAMS2778.1

MeteoSwiss, 2013: *Capacity Building and Twinning for Climate Observing Systems (CATCOS) – Glacier Monitoring*. http://www.meteoschweiz.admin.ch/web/en/meteoswiss/international_affairs/international_projects/CATCOS.html

Miller, B. R., R. F. Weiss, P. K. Salmeh, T. Tanhua, B. R. Greally, J. Mühle, and P. G. Simmonds, 2008: Medusa: A Sample Preconcentration and GC/MS Detector System for in Situ Measurements of Atmospheric Trace Halocarbons, Hydrocarbons, and Sulfur Compounds. *Anal. Chem*.**, 80**, 1536-1545.

Mühle, J., A.L. Ganesan, B.R. Miller, P.K. Salameh, C.M. Harth, B.R. Greally, M. Rigby, L.W. Porter, L.P. Steele, C.M. Trudinger, P.B. Krummel, S. O'Doherty, P.J. Fraser, P.G. Simmonds, R.G. Prinn, and R.F. Weiss, 2010: Perfluorocarbons in the global atmosphere: Tetrafluoromethane, hexafluoroethane, and octafluoropropane. *Atmos. Chem. Phys*., 10, 5145–5164.

Nelson, B., 2009: Empty archives. *Nature*, **461**, 160-163.

Nilsson, M., and H. Dalkmann, 2001: Decision Making and Strategic Environmental Assessment. *Journal of Environmental Assessment Policy and Management* **03** (3), 305 (2001). doi: 10.1142/S1464333201000728

Nisbet, E., 2007: Cinderella science. *Nature*, **450**, 789-790.

NRC, 1994: *Ocean-Atmosphere Observations Supporting Short-Term Climate Predictions*. National Research Council, National Academy Press, Washington, DC, USA, 51pp.

Pereira, H. M., S. Ferrier, M. Walters, G. N. Geller, R. H. G. Jongman, R. J. Scholes, M. W. Bruford, N. Brummitt, S. H. M. Butchart, A. C. Cardoso, N. C. Coops, E. Dulloo, D. P. Faith, J. Freyhof, R. D. Gregory, C. Heip, R. Höft, G. Hurtt, W. Jetz, D. S. Karp, M. A. McGeoch, D. Obura, Y. Onoda, N. Pettorelli, B. Reyers, R. Sayre, J. P. W. Scharlemann, S. N. Stuart, E. Turak, M. Walpole, and M. Wegmann, 2013: Essential Biodiversity Variables. *Science* 339, 277-278.

Peterson, T., H. Daan, and P. Jones, 1997: Initial Selection of a GCOS Surface Network. *Bull. Amer. Met. Soc*. **78**, No. 10, October 1997, pp. 2145-2152.

Peterson, T. C., K.P. Gallo, J. Lawrimore, T.W. Owen, A.Huang, and D.A. McKittrick, 1999: Global rural temperature trends. *Geophysical Research Letters*, **26**, 329-332.

Peterson, T.C., and J. F. Griffiths, 1997: Historical African data. *Bull. Amer. Meteor. Soc.*, **78**, 2869-2872.

Schulz, J., P. Albert, H.-D. Behr, D. Caprion, H. Deneke, S. Dewitte, B. Dürr, P. Fuchs, A. Gratzki, P. Hechler, R. Hollmann, S. Johnston, K.-G. Karlsson, T. Manninen, R. Müller, M. Reuter, A. Riihelä, R. Roebeling, N. Selbach, A. Tetzlaff, W. Thomas, M. Werscheck, E. Wolters, and A. Zelenka, 2009: Operational climate monitoring from space: The EUMETSAT Satellite Application Facility on Climate Monitoring (CM-SAF). *Atmos. Chem. Phys.*, **9**, 1687–1709.

Seidel, D.J., F.H. Berger, H.J. Diamond, J. Dykema, D. Goodrich, F. Immler, W. Murray, T. Peterson, D. Sisterson, M. Sommer, P. Thorne, H. Vömel, and J. Wang, 2009: Reference Upper-Air Observations for Climate – Rationale, Progress, and Plans. *Bull. Amer. Meteor. Soc.*, **90**, 361-369.

Seiz, G., and N. Foppa, 2007: *National Climate Observing System (GCOS Switzerland)*. Publication of MeteoSwiss and ProClim, 92 pp. available at http://www.meteosuisse.admin.ch/web/en/meteoswiss/international_affairs/gcos/uebersicht_klimabeobachtung/nationales_klimabeobachtungssystem.Par.0027.DownloadFile.tmp/nationalclimateobservingsystem.pdf

Shapiro, M., J. Shukla, G. Brunet, C. Nobre, M. Béland, R. Dole, K. Trenberth, R. Anthes, G. Asrar, L. Barrie, P. Bougeault, G. Brasseur, D. Burridge, A. Busalacchi, J. Caughey, D. Chen, J. Church, T. Enomoto, B. Hoskins, Oe. Hov, A. Laing, H. Le Treut, J. Marotzke, G. McBean, G. Meehl, M. Miller, B. Mills, J. Mitchell, M. Moncrieff, T. Nakazawa, H. Olafsson, T. Palmer, D. Parsons, D. Rogers, A. Simmons, A. Troccoli, Z. Toth, L. Uccellini, C. Velden, and J.M. Wallace, 2010: An Earth-System Prediction Initiative for the Twenty-First Century. *Bull. Amer. Meteor. Soc.,* **91**, 1378-1388, October 2010. doi:10.1175/2010BAMS2944.1

Simmons, A., K. M. Willett, P. D. Jones, P. W. Thorne, and D. P. Dee, 2010: Low-frequency variations in surface atmospheric humidity, temperature, and precipitation: Inferences from reanalyses and monthly gridded observational data sets. *J. Geophys. Res.,* 115, D01110. doi:10.1029/2009JD012442

Smith, S. L., J. Throop, and A. G. Lewkowicz, 2012: Recent changes in climate and permafrost temperatures at forested and polar desert sites in northern Canada. *Can. J. Earth Sci.*, **49**, 914-924.

Spencer, R.W., and J.R. Christy, 1990: Precise monitoring of global temperature trends from satellites. *Science* 247:1558–1562.

Stubenrauch, C. J., W. B. Rossow, S. Kinne, S. Ackerman, G. Cesana, H. Chepfer, L. Di Girolamo, B. Getzewich, A. Guignard, A. Heidinger, B. Maddux, P. Menzel, P. Minnis, C. Pearl, S. Platnick, C. Poulsen, J. Riedi, S. Sun-Mack, A. Walther, D. Winker, S. Zeng, and G. Zhao, 2013: Assessment of Global Cloud Datasets from Satellites: Project and Database initiated by the GEWEX Radiation Panel. *Bull. Amer. Meteor. Soc*., **94**, 1031–1049. doi: 10.1175/BAMS-D-12-00117

Thorne, P. W., J. R. Lanzante, T. C. Peterson, D. J. Seidel, and K. P. Shine, 2010: Tropospheric temperature trends: History of an ongoing controversy, *WIREs Climate Change*. doi:10.1002/wcc.80

Trenberth, K., 1995: Long-term climate monitoring by the Global Climate Observing System; Report of Break-out Group B – Climate Responses and Feedbacks. *Climatic Change* 31: 163-180.

Trenberth, K.E., R.A. Anthes, A. Belward, O. Brown, E. Haberman, T.R. Karl, S. Running, B. Ryan, M. Tanner, and B. Wielicki, 2012: Challenges of a sustained climate observing system. In *Climate Science for Serving Society: Research, Modelling and Prediction Priorities*, Hurrell, J.W. and Asrar, G., Eds., Springer, 485p. ISBN 978-94-007-6691-4.

Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson, and M. Prather, 2007: Historical Overview of Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Uhlir, P.F., R.S. Chen, J.I. Gabrynowicz, and K. Janssen, 2009: Towards Implementation of the Global Earth Observation System of Systems Data Sharing Principles. *Journal of Space Law* **35**(1), 201-290.

UNESCO, 1972: *Convention Concerning the Protection of the World Cultural and Natural Heritage*. Adopted by the General Conference at its seventeenth session, Paris, 16 November 1972, available at http://whc.unesco.org/archive/convention-en.pdf

UNESCO, 2012: *A Framework for Ocean Observing.* By the Task Team for an Integrated Framework for Sustained Ocean Observing, IOC/INF-1284. doi: 10.5270/OceanObs09-FOO

UNFCCC, 2004: *Report of the Conference of the Parties on its ninth session, held at Milan from 1 to 12 December 2003,* Addendum, Part two: Decision 11/CP.9 (Global observing systems for climate), paragraph 8, FCCC/CP/2003/6/Add.1. available at http://unfccc.int/resource/docs/cop9/06a01.pdf#page=20

UNFCCC, 2008: *Report of the Conference of the Parties on its thirteenth session, held in Bali from 3 to 15 December 2007*, Addendum, Decision 11/CP.13 (Reporting on global observing systems for climate), FCCC/CP/2007/6/Add.2.available at http://unfccc.int/resource/docs/2007/cop13/eng/06a02.pdf#page=1

UN, 2012: *The future we want* – Resolution 66/288 adopted by the United Nations General Assembly at its 66th session, September 2012. available at http://sustainabledevelopment.un.org/futurewewant.html

WCRP, 2011: *Report of WOAP Workshop on Evaluation of Satellite-Related Global Climate Datasets*. Frascati, Italy, 18-20 April 2011. WCRP Informal Report 33/2011, GCOS-153. available at http://wcrp-climate.org/documents/ECV_Wksp_WCRP_Report.pdf

WGMS, 2008: *Global Glacier Changes: facts and figures*. M. Zemp, I. Gärtner-Roer, A. Kääb, M. Hoelzle, F. Paul, and W. Haeberli, Eds., pp. 88, Zurich, Switzerland, UNEP, World Glacier Monitoring Service. available at http://www.grid.unep.ch/glaciers/

Widlowski, J.-L., 2010: On the bias of instantaneous FAPAR estimates in open-canopy forests. *Agricultural and Forest Meteorology*, **150**(12): 1501-1522. doi: 10.1016/j.agrformet.2010.07.011

WMO, 2009: Better climate information for a better future, World Climate Conference-3, Third Announcement. WMO Secretariat: Geneva, Switzerland, p 24.

WMO, 2011a: *Climate knowledge for action: A global framework for climate services, empowering the most vulnerable*, World Meteorological Organization, Report No. 1065, Geneva, Switzerland. http://www.wmo.int/hlt-gfcs/downloads/HLT_book_full.pdf.

WMO, 2011b: *Guide to Climatological Practices, 2011 edition*. World Meteorological Organization, Report No. 100, Geneva Switzerland. http://www.wmo.int/pages/prog/wcp/ccl/documents/WMO_100_en.pdf

WMO, 2012: *WMO Integrated Global Observing System – Final Report of the Fifth WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction*. Sedona AZ, USA, 22-25 May 2012. WMO Technical Report No. 2012-1. https://www.wmo.int/pages/prog/www/OSY/Meetings/NWP5_Sedona2012/Final_Report.pdf

WMO, 2013: *The Global Climate 2001-2010 - a decade of climate extremes*. World Meteorological Organization, WMO-No. 1103.

Wunsch, C., R.W. Schmitt, and D.J. Baker, 2013: Climate change as an intergenerational problem. *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* 110 (12), 4435-4436, available at http://www.pnas.org/cgi/doi/10.1073/pnas.1302536110

Zemp, M., E. Thibert, M. Huss, D. Stumm, C. Rolstad Denby, C. Nuth, S. U. Nussbaumer, G. Moholdt, A. Mercer, C. Mayer, P. C. Joerg, P. Jansson, B. Hynek, A. Fischer, H. Escher-Vetter, H. Elvehøy, and L. M. Andreassen, 2013: Reanalysing glacier mass balance measurement series. *The Cryosphere,* **7***,* 1227-1245*,* doi:10.5194/tc-7-1227-2013.

Side Bar: Building ECV datasets for climate monitoring

One key application to be addressed by the ECVs is climate monitoring, i.e. assessing climate variability and change using long time series of observations. Building an ECV dataset suitable for monitoring is generally complex. Typical steps are:

Assembling the data This first step may be straightforward for some *in situ* ECV datasets where the observations have already been taken and assembled as part of large data collections (e.g., surface water vapour; Willet et al. 2013). Alternately, it may involve analyzing satellite observations spanning a decade or more to extract broad-scale representations of upper-air temperature (Spencer and Christy 1990). Some ECVs, such as the long-lived and strongly infrared-absorbing perfluorocarbons (PFCs), may require new observing instrumentation for accurate monitoring (Miller et al. 2008) that can also be used to extend the ECV record into the past by assessing archived gas (Mühle et al. 2010). Additionally, ECVs such as surface temperature may require searching archives and digitizing historical paper records to improve spatial or temporal coverage (e.g. Peterson and Griffiths 1997).

Adjusting data to account for inhomogeneities In addition to spurious errors in individual data values, which good quality control tests can remove, there are few long-term ECV observations that do not suffer from inhomogeneities unrelated to climate. Examples are drifts in satellite orbits over time and changes in observing practice: for example, ship-based sea surface temperature observations changed from putting thermometers in buckets that had been tossed overboard to haul up water from the surface of the ocean to thermometers being placed in engine cooling water intakes which, for large ships, are typically located 5-15 m below the surface (Kent and Kaplan 2006). There exist many techniques to adjust climate time series data to account for such artificial inhomogeneities (e.g. Aguilar et al. 2003).

Real-time updates Regular updates of an ECV dataset are required if the dataset is to be used for monitoring changes in the ECV. Operationally updating a dataset is a very different process requiring different skill sets than conducting the homogeneity research. It also marks the transition from research to operations.

Post-production quality assurance There are many different aspects to this stage. It often involves scrutinizing the data to assess particular characteristics of the ECV record. For example, for surface temperature, do rural stations indicate the same changes as the dataset as a whole (e.g., Peterson et al. 1999)? Or do permafrost temperatures increase when winter air temperatures increase (e.g., Smith et al. 2012)? Did sensor degradation or aerosols from volcanic eruptions artificially change a satellite-derived leaf area index (Los et al. 2000)? This stage also involves evaluating real-time updates to correct for other errors, for example in the metadata (Lawrimore et al. 2011).

Documentation and transparency As the IPCC 4th Assessment Report states, "scientists usually submit their research findings to the scrutiny of their peers, which includes disclosing the methods that they use, so their results can be checked through replication by other scientists" (Le Treut et al. 2007). However, given the central role that ECVs are increasingly having in monitoring the global climate, a higher level of transparency is generally expected to ensure credibility, as stated in the Introduction. For example, rather than just providing the data and describing the algorithms used to produce the dataset, providing public access to the actual computer code used to make the ECV dataset is now part of what is considered best practice (Bates and Privette 2012).

More than one dataset per ECV is required After over a decade of producing an upper-air temperature record, with a series of successive improvements (Christy et al. 2003), another group undertook the creation of a satellite-derived record for this ECV. In the process of producing their version (Mears et al. 2003), they uncovered an error in the first group's adjustment to account for satellite drift, an error that changed the sign of the adjustment (Thorne et al. 2010). This example illustrates that the best proof of quality is having several independent groups producing their own versions of ECV datasets, ideally using different methodologies, as this would help quantify the structural uncertainty in the ECV records as well as provide objective, empirical corroboration of the results (Folland et al. 2006).

Monitoring the ECV A key need is to understand how the ECVs are changing. The *State of the Climate* report (Blunden and Arndt 2013) provides an annual reference based on a large community effort that assesses change for many ECVs and other climatic variables. Not only does co-authoring that paper provide an opportunity for scientists to update their results annually, but because the report includes multiple alternative ECV datasets wherever possible, it allows ready comparison of the results of different groups.

Table 1: The Essential Climate Variables (GCOS-138 2010, which gives qualifying details). Indices indicate the following: a) including measurements at standardized, but globally varying heights in close proximity to the surface; b) up to the stratopause; c) including N_2O, CFCs, HCFCs, SF_6, and PFCs; d) in particular NO_2, SO_2, HCHO and CO; e) including measurements within the surface mixed layer, usually within the upper 15m.

Atmospheric	**Surface[a]:**	Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget
	Upper-air[b]:	Temperature, wind speed and direction, water vapour, cloud properties, earth radiation budget (including solar irradiance)
	Composition:	Carbon dioxide, methane, other long-lived greenhouse gases[c], ozone and aerosol supported by their precursors[d]
Oceanic	**Surface[e]:**	Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, surface current, ocean colour, carbon dioxide partial pressure, ocean acidity, phytoplankton
	Sub-surface:	Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers
Terrestrial		River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire disturbance, soil moisture

FIGURE CAPTIONS

Figure 1: The role of observation within the Global Framework for Climate Services (GFCS) and in support of research, the assessment of climate change, in particular as undertaken by the Intergovernmental Panel on Climate Change (IPCC), and the development and implementation of policy responses, in particular under the United Nations Framework Convention on Climate Change (UNFCCC). Grey arrows denote the main directions of flow of climate data and derived information. Feedback for system improvement flows mainly in the opposite direction. The GFCS includes a substantial capacity-development component that underlies all illustrated components. Adapted from WMO (2009, 2011a).

Figure **2:** Schematic of the ECV concept: knowing existing climate-relevant observing capabilities, climate datasets, and the level of scientific understanding of the climate system are the foundations (lower left box) necessary for selecting the ECVs from a pool of climate system variables. In addition, guidance is needed to make practical use of the ECVs (lower right box): user requirements capture the data quality needs of science, services and policy; climate-specific principles guide the operation of observing systems and infrastructure; guidelines facilitate the transparent generation of ECV data records. The latter address the availability of metadata, provisions for data curation and distribution, and the need for quality assessment and peer review.

Figure 3: Process for regularly reviewing the ECV concept, under GCOS programme auspices. At around six year intervals, the adequacy of climate observations, datasets, and related infrastructure (e.g., archives) is assessed, using feedback from ECV dataset users. Updated plans for implementation should result in improved ECV dataset generation and exploitation. Each iteration of the cycle considers emerging climate system variables in the "variable pool" for their relevance, feasibility and cost-effectiveness of observation. This cycle is generic and could serve as a model for other observation types.

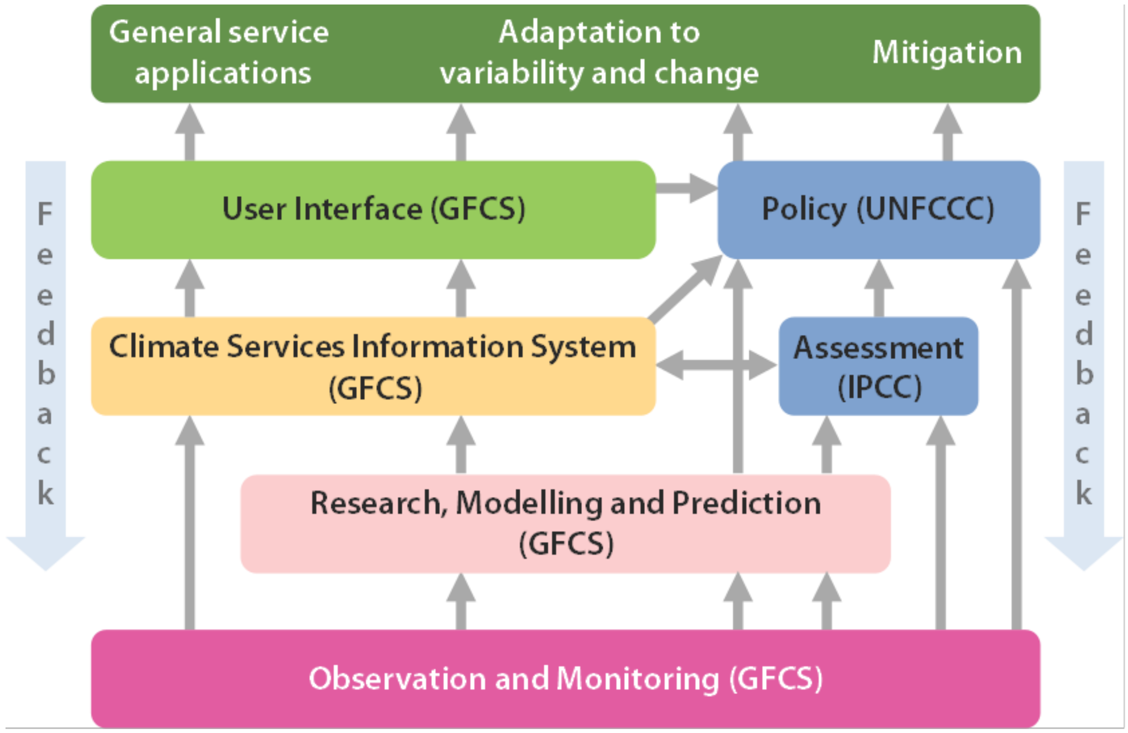

Figure 1: The role of observation within the Global Framework for Climate Services (GFCS) and in support of research, the assessment of climate change, in particular as undertaken by the Intergovernmental Panel on Climate Change (IPCC), and the development and implementation of policy responses, in particular under the United Nations Framework Convention on Climate Change (UNFCCC). Grey arrows denote the main directions of flow of climate data and derived information. Feedback for system improvement flows mainly in the opposite direction. The GFCS includes a substantial capacity-development component that underlies all illustrated components. Adapted from WMO (2009, 2011a).

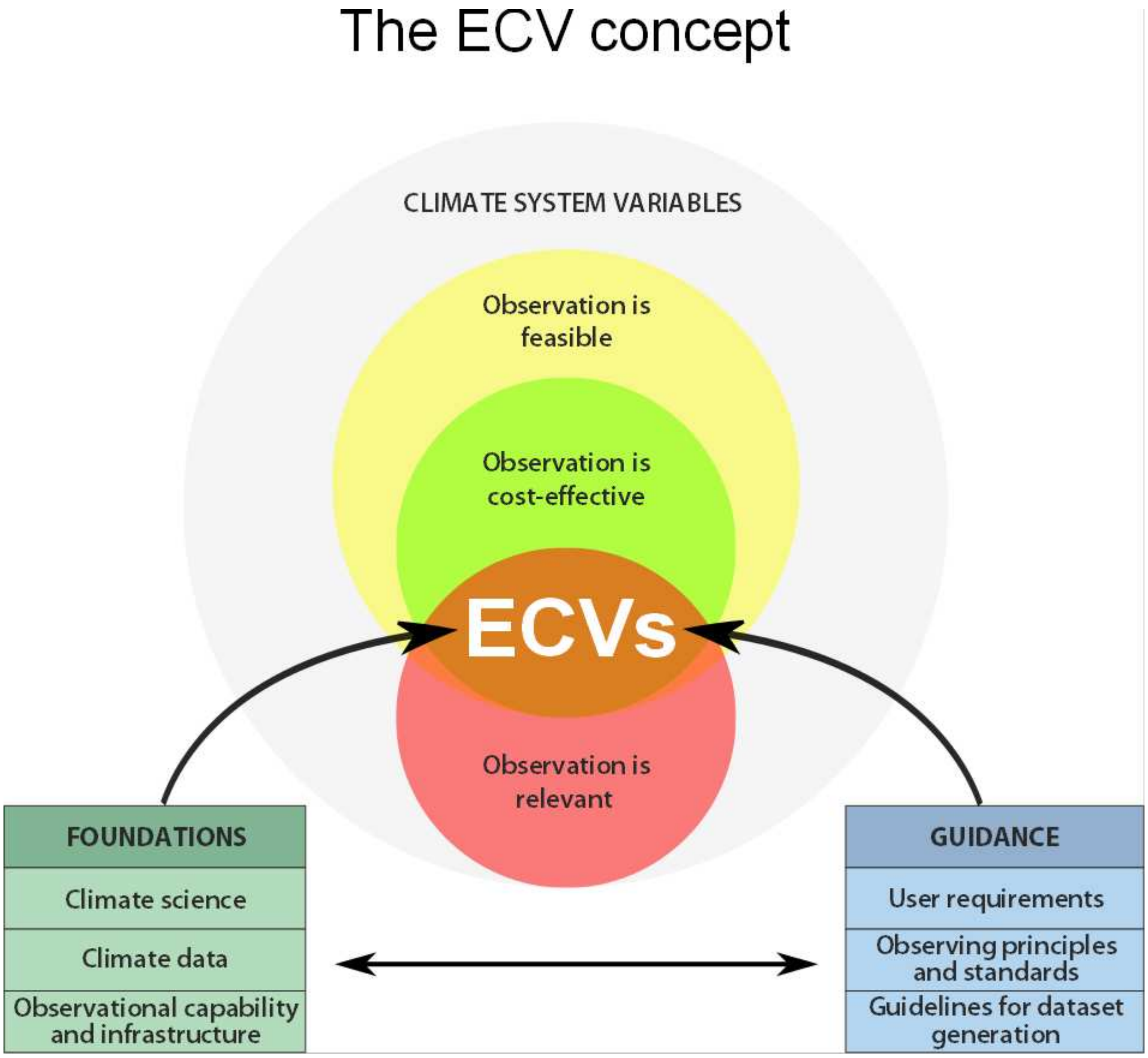

Figure 2**:** Schematic of the ECV concept: knowing existing climate-relevant observing capabilities, climate datasets, and the level of scientific understanding of the climate system are the foundations (lower left box) necessary for selecting the ECVs from a pool of climate system variables. In addition, guidance is needed to make practical use of the ECVs (lower right box): user requirements capture the data quality needs of science, services and policy; climate-specific principles guide the operation of observing systems and infrastructure; guidelines facilitate the transparent generation of ECV data records. The latter address the availability of

metadata, provisions for data curation and distribution, and the need for quality assessment and peer review.

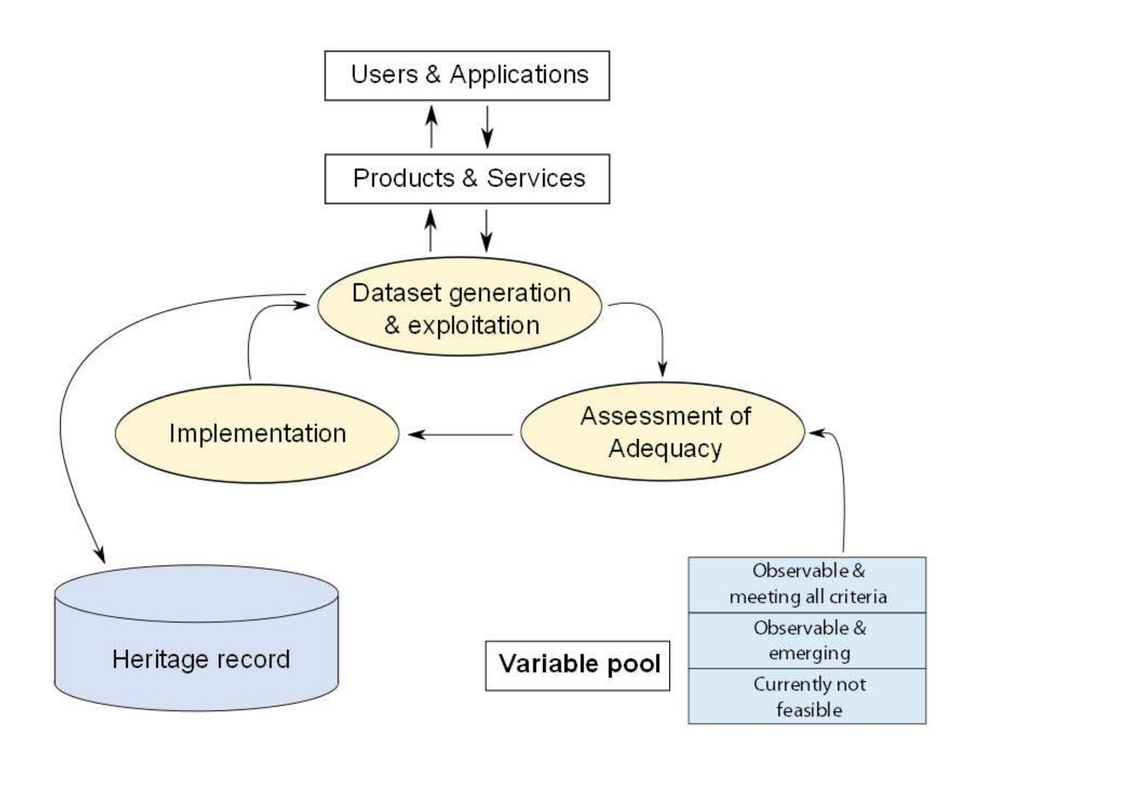

Figure 3: Process for regularly reviewing the ECV concept, under GCOS programme auspices. At around six year intervals, the adequacy of climate observations, datasets, and related infrastructure (e.g., archives) is assessed, using feedback from ECV dataset users. Updated plans for implementation should result in improved ECV dataset generation and exploitation. Each iteration of the cycle considers emerging climate system variables in the “variable pool” for their relevance, feasibility and cost-effectiveness of observation. This cycle is generic and could serve as a model for other observation types.